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14. ABSTRACT
The overall objective of this research was to contribute to the advancement of technologies to support affordable Human Behavior Modeling. In support of this effort we looked at a number of related issues. One of these was the development of improved computational learning technologies. Another was the construction of a unified framework for the representation and subsequent manipulation of various types of uncertain information. We investigated the development of operators that allow the logical and arithmetic manipulation of uncertain information and the fusion of uncertain information coming from multiple sources.

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The need to model uncertain information arises in many tasks in our modern technological environment. Further compounding the situation, is the fact that in many current technological applications uncertain information can appear, not only in the classic probabilistic format, but can come in many different modalities. We have investigated the use of a monotonic set measure, fuzzy measure, for the representation of uncertain information about the value of a variable. The use of a fuzzy measure to represent uncertain information provides a unified framework for the representation of many different modes of uncertain information. This is particular useful in the task of multi-source information fusion and decision making under uncertainty. Given our large body of experience in working in the probabilistic environment we focused on formulating some of the important concepts and methodologies used in the probabilistic environment in the framework of a measure based representation of uncertain information. We showed how the Choquet integral could be used to move an idea similar to expected value to the measure representation environment. We looked at the important application of this to the problem of decision-making under measure based-uncertainty. More generally we showed that the Choquet could be used to obtain an expected-like value for any function of a measure type uncertain variable. This immediately allows us to formulate the concept of variance in this measure environment.

Conditioning is a useful operation in modern information processing. It is central to the very popular Bayes rule. Another paradigm for conditioning is the Jeffrey rule of conditioning. It provides a procedure for determining the probability of an event A associated with one variable, for example U, based upon a collection of conditional probabilities of A conditioned upon the state of another variable V. The conditioning states of V, B_j for j = 1 to q, form a partition of the space associated with V. For example A may correspond to presence of a particular disease and the variable V corresponds the results of a test and the conditionals are probability of having the disease for particular test result. Jeffrey's rule allows for some uncertainty about the knowledge of state of the variable V. Thus while we know the conditional probability of A given the state of V we are not sure of the state of V. In the original Jeffrey work it is assumed that the knowledge about the state of V is carried by a probability distribution over the partitioning sets, the B_j. We extended this framework by allowing alternative formulations for the uncertainty about the conditioning variable. We first considered the case where our uncertainty is expressed in terms of a measure. This allowed us to consider the case where our uncertainty is a possibility distribution. We also considered the case where our uncertainty about the conditioning variable is expressed in terms of a Dempster-Shafer belief structure. Finally we considered the case where we are ignorant about the underlying distribution and must use the decision maker's subjective attitude about the nature of uncertainty to provide the necessary information to use in the Jeffrey rule.

Decision-making problems in environments in which the payoff resulting from the selection of an alternative is uncertain are very pervasive. The most common form for the representation of the uncertainty is a probabilistic framework. The comparison of alternatives with uncertain payoffs is not easy and hence the determination of the alternative that gives the biggest payoff is difficult. A well-regarded method for comparing two alternatives in the case of probabilistic uncertainty is to use stochastic dominance. We recall alternative A stochastically dominates alternative B if for any value of payoff x, alternative A has at least as high a probability of resulting in a payoff greater then or equal x then does alternative B. One problem is that stochastic dominance is a strong condition and generally a stochastic dominance relationship does not exist between two alternatives, neither one stochastically dominates the other. In order to provide operational decision tools to compare alternatives we looked for surrogates for stochastic dominance. These surrogates associate with each alternative a numeric value, the larger the value the more preferred. In our previous work we looked at the formulation of surrogates for stochastic dominance. Here we investigated a generalization of these ideas to case the where the uncertainty associated with an alternative's payoff is represented using a measure. In this case our first task was to extend the concept of stochastic dominance to case where the uncertain payoffs being compared are measure based. Here again the relationship of stochastic dominance between uncertain alternatives is a strong condition and we had to turn to surrogates for comparing alternatives. We defined the properties of a class of surrogates for the case of measure based stochastic dominance that we referred to as *Measure Weighted Means*. We then used these properties to develop a number of formulations for measure weighted means.

Assuring systems reliability is a very important and complex task for large-scale organizations such as the Navy. It requires the use of sophisticated ideas and theory. The better we understand these ideas and the more tools we have at our disposal the more our opportunity for accomplishing our objectives. System reliability theory is a collection of concepts and mathematical models whose focus is on predicting and optimizing the proper functioning of systems of interrelated components that can deteriorate and fail in the course of time. Propositional logic is often used to model the structure and interrelationship between the components of a system. Probability theory plays a fundamental role in providing distributions to help model performance features of the individual elements in a complex system. The confluence of these two disciplines is at the heart of the technologies to study system's reliability. One framework for studying reliability involves the use of systems signatures. Fundamental to modeling a system's reliability is the system's structure function, which is a mapping from states of the individual components, working or not working, to the state of the whole system. An important issue in reliability is the comparison of different systems structures with respect their reliability. In an attempt to give us more tools to deal with reliability issues we investigated how these system structure functions can be modeled using a fuzzy measure. We showed how some concepts from the perspective of fuzzy measure theory could be used to provide tools to compare the reliability of complex systems.

We looked at a problem in group decision making where we have a number of individual agents each of who have their own opinion about the subjective probability distribution with respect to the occurrence of an outcome from a finite set X possible outcomes. Our objective was to interactively combine the opinions of these individual agents about this subjective probability distribution to obtain the group consensus subjective probability distributions. We developed an approach in the spirit of the interactive Delphi Method but one having a more formal mechanism. The method used iterative rounds where the agents can provide modified versions of their subjective probability distribution that allows them to take into account the current group aggregated probability distribution. At each round we aggregated the individual agents subjective probability distributions to obtain a current group consensus. The rounds of iterations continued until the aggregated group consensus probability distribution converged to limit value. In order to encourage this convergence our system had a mechanism that rewarded those agents whose revised subjective probability distributions are the most compatible with the current group aggregated probability distribution from the previous iteration. We showed that the approach is very suitable for various types of internet-based negotiations involving distributed agents.

Conditional probability provides a very useful tool for modifying "a priori" probability information about a decision variable of interest based upon probability information of a related variable. This can be particularly valuable in decision-making tasks where the conditioned probability provides more informed knowledge about the environment and hence enables better decisions. Implicit in the formulation of the conditional probability is the requirement of having information about the joint probabilities of the conditioned and conditioning variables. A useful result that can help us in obtaining these joint probabilities is contained in the Sklar theorem. This theorem provides a direct way of obtaining the joint cumulative distribution function from the two marginal cumulative distribution functions by a simple binary aggregation of these marginals using a copula, which is a kind of "anding" operator. Here the choice of the copula is a reflection of the type of correlation between the conditioned and conditioning variables. Recalling that a cumulative distribution function expresses the probability that a variable is less then or equal a value, Prob($U \leq x$), we focused on the calculation of conditional probabilities of the form Prob($U \leq x | V \leq y$). Since Prob($U \leq x$, $V \leq y$) = is essentially the determination of a joint cumulative distribution from marginal cumulative distributions we were able to take advantage of the Sklar theorem to calculate these conditional probabilities. We first looked at this under the use of different copulas. A further useful result we obtained was that in the discrete environment we can directly calculate the probability that $U = x_i$ conditioned on the knowledge of the Prob($V \leq y$). We illustrated the use of this in the case of decision-making under uncertainty where we can compare an alternative's expected payoffs based on the conditioned probabilities.

Multi-criteria decision-making arises in many tasks. During our research we began investigating one approach to the problem of multi-criteria decision-making based the use of a monotonic set measure μ, fuzzy measure, to formalize information about complex importance relationships between the multi-criteria. Using this we looked at how to express the importance of a set A of criteria as the measure A. Using this information we investigated how the aggregation of an alternative's individual criteria satisfactions can be used to obtain the alternative's overall satisfaction to the multiple criteria. We looked at how this aggregation can be accomplished by the use of some discrete integral like operation such as the Choquet and Sugeno integrals. Our objective was to get a deeper understanding of the role and properties of fuzzy measures in the construction of multi-criteria decision functions. Among the important properties required of such aggregation operations is monotonicity with respect to criteria satisfaction, as an alternative's satisfaction to the individual criteria increases its overall satisfaction cannot decrease. We focused on a special class of measures called quasi-additive measures. We looked at the process of building complex models of multi-criteria importance by constructing measures from other measures. We looked at the process of evaluating alternatives based on the measure representation of criteria importance. We introduced a relationship between measures, $\mu_1 > \mu_2$, and investigated how this effects the relationship between their respective valuation of alternatives.

The Dempster-Shafer belief structure provides a framework for representing uncertain information about the value of a variable. It is particularly applicable in situations in which the information about the uncertainty contains aspects of both randomness and granular imprecision. A particular important task in use of these belief structures is the combining of information from multiple sources. Here we looked at a number of types of combination of belief structures. The first, which we referred to as fusion, occurs when the information being combined are about the same variable. Here the result is some belief structure about the variable of interest. The second type, which we referred to as joining, occurs when the information being combined are about the different variables. Here we obtain a joint belief structure. In this case we showed how use can be made of copulas to implement the aggregation of the associated cumulative distribution functions. In the final part of this work we looked to extend the representational capability of the D-S belief structure by allowing for belief structures in which we can have a continuum of focal elements. Among other things this allowed us to model imprecise probability density functions. We showed how to combine these types of continuum based belief structures.

Relationships such as *much greater than*, *slightly greater than* and *about equal* are pervasive in human reasoning and decision-making. Fuzzy mathematics can play an important role in modeling these kinds of soft relationship commonplace in human cognition. We investigated the mathematical structure of relationships. We looked at some important examples of mathematical relationships and described their formal properties. We looked at the problem of calculating the degree of relationship between attributes whose values are uncertain. If we have a relationship corresponding to *approximately the same* with regard to concept of age then if A and B are two people whose ages we know we can easily calculate the degree to which A and B's ages are approximately the same. Our concern was with a more complex problem. Here rather than knowing the exact ages of the two people our knowledge of their ages was uncertain.

Thus here we have two uncertain variables U and V corresponding to A and B's ages and we are interested in determining the degree to which these uncertain variables satisfy the relationship of being a approximately the same. We look at this problem for cases where the uncertain information takes the form of a possibility distribution, probability distribution as well as a Dempster-Shafer belief structure .

The use of fusion to combine data provided by multiple sources about the value of a variable is a common in many military applications. One rational for fusing probabilistic distributions provided by multiple sources is to improve the quality of the information to decision makers. Our interest was in looking at the problem of obtaining high quality fused values in the case of probabilistic information. One aspect of quality is a reduction in the uncertainty in the information provided by the individual sources. Unfortunately combining probability distributions information does not always result in a probability distribution with less uncertainty, this is particularly the case when the data that is being fused is conflicting. In order to formally quantify the uncertainty associated with a probability distribution we used the concept of entropy. A second factor associated with quality of a fused value is that we use as many of the reliable sources of information as possible, the more reliable information sources used the more credible the results of the fusion process. In order to capture this criteria in quality fusion we introduced a measure of credibility associated with use of various subsets of the sources. We provided a quantification of the notion of a quality fusion based on the objective of providing fused values having little uncertainty and based on a credible subset of the sources. Our objective here was to obtain a measure of quality-fused values from multiple sources of probabilistic distributions, where quality is related to the lack uncertainty in the fused value and the use of credible sources. We introduced a vector representation for a probability distribution and with the aid of the Gini formulation of entropy we showed how the norm of the vector provides a measure of the certainty, the information associated with a probability distribution. We look at special cases of fusion for source inputs that are maximally uncertain and certain. We look at the issue of finding the highest quality fused value from the weighted aggregation of multi-source provided probability distributions.

Multi-criteria decision problems are pervasive. They arise in such simple tasks as deciding what journal you want to submit a paper to and such complex tasks as a drone tracking a target. In these applications the decision maker has some objective related to a relevant set of multiple criteria. In many cases the decision maker's objective function can be expressed in terms of a fuzzy measure μ over the set of multiple criteria. We focused on the use of a measure to represent these decision maker objective functions. For example in deciding which journal to submit his paper a researcher may consider the following criteria relevant high impact factor, fast review time and good chance for acceptance. One formulation for his objective function may be to select a journal that satisfies all these criteria. Another formulation for his objective could be to associate with each criterion an importance weight and then look for the alternative that provides maximal weighted satisfaction to his criteria. Either of these objectives can be expressed in terms of a fuzzy measure over the set of criteria.

In addition to their objective function a decision maker has available a collection of possible alternative actions they can take. Here we must decide which alternative action to choose based upon its satisfaction to the decision maker's objective function as manifested through an alternatives satisfaction to the individual criteria. We considered how we could obtain the satisfaction of an alternative to the decision maker's objective function by calculating the integral, with respect to the measure μ, of the alternatives satisfactions to relevant criteria. Here the integral provides a kind weighted average of individual criteria satisfactions were the weights are determined by the fuzzy measure modeling the decision maker's objective function.

We look at several finite integrals useful for obtaining an average value of a collection of argument values weighted by a measure. We particularly look at the case of binary measures and show that all integrals in this case evaluate to the same value. We describe the use of measures in multi-criteria decision making as a way of expressing a decision maker's objective function in terms of collection of relevant criteria. We look at the role of integral as a way to evaluate an alternative's overall satisfaction to their objective function in terms of its satisfaction to the individual criteria. We look at a number of special types of measure based decision objective functions.

A recently emerging area of Cyber strategy is moving target defense where we are interested in including uncertainty in our cyber systems to confuse enemy attackers. During this research we looked at the role that the Dempster-Shafer theory can play in this approach. Our point of departure here is a system whose output is a variable V whose value is expressed using a Dempster-Shafer belief structure it can be both imprecise and random. Our objective is the determination of the degree to which the system output V satisfies some target value that can be uncertain. We consider various different formulations for the target value. Among those target types considered were probability distributions, belief structures, measures and possibility distributions. At a formal level this work involved the extension of the concepts of plausibility and belief associated with D-S structures from being mappings of subsets of the underling domain of V into unit interval to be mappings of these more complex structures into the unit interval. Thus, for example, if our system output is a belief structure m and our target value is also described using a belief structure, m_1, then our interest is in determining $Pl_m(m_1)$ and $Bel_m(m_1)$, the plausibility and belief of m_1 under m. Once having these can we obtain an interval valued solution, $[Bel_m(m_1), Pl_m(m_1)]$, as the determination of the degree to which m satisfies the target m_1.

Central to multi-criteria decision-making is the aggregation of an alternative's satisfactions to the individual criteria to obtain its overall satisfaction to the task of interest. One commonly used method for performing this aggregation is the Ordered Weighted Averaging (OWA) Operator. Here the arguments in the OWA aggregation are the individual criteria satisfactions. In our research we looked at the situation in which there exists some probabilistic uncertainty associated with the criteria satisfactions. The criteria satisfactions are probability distributions over a finite domain. This required that we must perform the OWA aggregation for the case where the arguments are discrete probability distributions. A central feature of the OWA operator is an ordering of the arguments being aggregated based upon their values, the bigger value the higher in the ordering. This then requires that we obtain an ordering over these probability distributions, a not necessarily easy task. One possible approach for obtaining a linear ordering over a collection of finite probability distributions is to use stochastic dominance. This requires a pairwise comparison of individual probability distributions to determine whether one stochastically dominates another. Using these pairwise comparisons we can get a binary relationship over the probability distributions from which we can generate the desired linear ordering. A problem that arises here is that often the relationship in not complete, there are pairs of probability distributions for which neither stochastically dominates the other; as a result we can not obtain the required linear ordering. One way the address this problem is to provide a surrogate for the OWA aggregation of probability distributions, one that can be used even if we don't have the required linear ordering and is compatible with the OWA aggregation in the case in which there exists the required ordering. During this research we developed the Probabilistic Exceedance Method, PEM as a surrogate for the OWA aggregation of probability distributions that doesn't require a linear ordering over the probability distributions. We look at this in both the cases in which the criteria have equal and unequal importances.

The need to model uncertain information arises in many tasks facing Naval decision makers. Further compounding the situation, is the fact that in many current technological applications uncertain information can appear, not only in the classic probabilistic format, but can come in many different modalities. We continued to investigated the use of a monotonic set measure, fuzzy measure, for the representation of uncertain information about the value of a variable. The use of a measure to represent uncertain information provides a unified framework for the representation of many different modes of uncertain information. This is particular useful in the task of multi-source information fusion and decision maker under uncertainty. Given our large body of experience in working in the probabilistic environment it appeared only prudent to try to take advantage of this as we move to the more general measure representation of uncertain information. With this in mind we focused on formulating some of the important concepts and methodologies used in the probabilistic environment in the framework of a measure based representation of uncertain information.

We showed how the concept of entropy could be expressed in the case of a measure. We illustrated how the Choquet integral can be used to move an idea similar to expected value to the measure representation environment. We showed this has immediate application to the problem of decision maker under measure based-uncertainty. More generally we showed that the Choquet could be used to obtain an expected-like value for any function of a measure type uncertain variable. This immediately allowed us to formulate the concept of variance in this measure environment. In probability theory an important idea is the probability of an event, where an event A is crisp or fuzzy subset of the domain of the uncertain variable. Here, since the idea of measure is broader then that of probability, we used the less specific terminology of "anticipation" and provided for the anticipation of an event in an analogous manner to speaking of the probability of an event. We provide a formulation for the anticipation of an event that reduces to the probability of an event in the case where the measure is a probabilistic one. We looked at a method for aggregating fuzzy measures which results in fuzzy measures. This was shown to provide a basis for an approach to a measure based technology for the fusion of multi-source uncertain information.

The Ordered Weighted Average (OWA) operator provides a parameterized class of mean-like operators which be used to aggregate a collection of arguments. The parameterization is accomplished by the choice of the characterizing OWA weights that are multiplied by the argument values in a linear type aggregation. We investigated various ways of providing these characterizing OWA weights. Most notable among these are the use of a vector containing the prescribed weights and the use of a function called the weight generating function from which the characterizing can be extracted. In many applications such as data mining we are faced with situations in which the arguments being aggregated have different importances. This raises the issue of appropriately combining the individual argument weights with the characterizing weights of the operator to obtain operational weights to be used in the actual aggregation. Our goal here was looking at this issue of obtaining different methods of specification of the characterizing weights. This is of significance in that it allows users more freedom in choosing the most appropriate method for providing information to a system.

Fuzzy system modeling provides a computationally intelligent method for building models of complex systems and organizational dynamics. They have used in many applications especially in control. A fuzzy systems model uses a fuzzy rule base in which the antecedent conditions of the rules are expressed using fuzzy sets. Central to the use of these models is the determination of the satisfaction, firing level, of the antecedent conditions based on information about the associated variables, the input to the fuzzy model. For the most part this input information has been expressed also using fuzzy sets. Our purpose was to extend the capabilities of the fuzzy systems modeling technology by allowing a wider class of input information. We considered the case where the input information about an antecedent variable is expressed using a measure representation. A notable special case is a probability distribution. In providing this extension a particularly important issue that we addressed was the determination of the satisfaction (firing level) of a fuzzy set terms of a measure.

Geographic Information Systems (GIS) are employed extensively throughout governmental and industrial organizations for planning and decision-making. Typically underlying a GIS is a spatial database in which much of the information is imprecise and uncertain. Representation of uncertainty in geospatial data can viewed as a most important issue in the development of geographic information systems.

Computation of geometric quantities from uncertain spatial data must be applied to many of the applications for which a GIS is appropriate. A recent example of the impact of spatial imprecision is illustrated by the difficulties in the search for Malaysia Airlines Flight 370. This flight disappeared en route from Kuala Lumpur Malaysia to Beijing China in 2014 and there was considerable spatial uncertainty as to its location. A variety of estimates for a search area came from several sources with varied uncertainties such as preliminary radar fixes, Inmarsat satellite communications, airliner fuel capacity, etc. Finally the focus of the search shifted to the southern part of the Indian Ocean, west of Australia where a extensive, expensive search of the seafloor was conducted. The initial imprecise area of possible locations of the plane was wide and expansive. The seafloor terrain in these possible areas is complex and affects search techniques. A good mathematical specification of the uncertain location would have saved considerable time and expense in the search. During the research we investigated how to apply Dempster-Shafer theory to represent aspects of uncertainty in spatial data for possible use in GIS systems. Using this representation we were able to provide the basic definitions of imprecise coordinates, points and lines are given next. Using these definitions we showed how to compute geometric quantities such as line length, areas and line slope. The framework we began to develop in addition to providing tools for the manipulation of uncertain spatial data also provided a corresponding cognitive perspective in which analysts can reason and make decisions.

Fuzzy measures provide a very useful formulation for the representation of various types of knowledge. Particularly notable are their use in representing knowledge about an uncertain variable and modeling the relationship between criteria in multi-criteria decision making. They have also been recently used in reliability theory. We showed that these measures can play an important role in modeling imprecise information in the field of granular computing as they can be viewed as a type of granule. A measure conveys its information by assigning, to subsets of its underling space, a value typically from the unit interval. Thus if μ is a measure on a finite space X and A is a subset of X the measure provides the value $\mu(A)$. Thus a measure is a map $\mu: 2^X \rightarrow [0, 1]$. The semantics associated with this value is generally context dependent. During this research we looked at extending the usefulness of the measure representation of knowledge by considering the possibility of allowing a measure to assign a value in the unit interval to other measures on the same space.